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Abstract

For the various tuning as well as the ignition campaigns, targets on NIF need to be filled with gases, typically He and/or H_2. Fill-tubes that supply the two small chambers in the target, the capsule and the hohlraum, are micro-capillaries that are only 10s of microns in diameter and present significant impedance to flow. Knowledge of the exact pressure and gas composition in the capsule and the hohlraum is critical for fielding targets on NIF. This requires modeling of the gas flow through the capillary tubes, both at RT and cryogenic temperatures.
We present results from a comprehensive model and its experimental verification for a range of condition such as temperature and pressure.

Introduction

Two of the primary components of NIF targets are the capsule and the hohlraum, both of which need to contain gases with precise compositional and density requirements at about 18K. These chambers are supplied by micro-capillary filltubes whose dimensions are constrained by the various ICF physics and ice-layering requirements. In our current target design, the capsule fill-tube is comprised of two sections: a short borosilicate glass filltube with a 5um tip that penetrates the capsule through the laser-dilled hole and a longer polyimide-coated silica tube with an inner diameter of 30 um. The hohlraum is connected with two identical filltubes, both polyimide-coated silica tube with a 75 um ID. These fill-tubes are about 115mm long and need to be able to curve and bend to conform to the connect the target to its base. We use polyimide coated glass capillaries to achieve this as the coating protects any surface scratches from the moisture in the ambient environment and prevents premature failure.

These fill-tubes are used to fill the target both at room temperature and at cryogenic conditions. It is critical for us know the impedances of these fill-tubes for predicting and controlling the pressures and compositions inside the capsule or the hohlraum at any time. Both these volumes are small enough that it is practically impossible to make their measurments in-situ. It is therefore necessary to be able to model the flow into the capsule or the hohlraum so that we can simulate various situations that arise during operations on NIF.

Commercial software packages are available nowadays that use in-built models to predict the flow of fluids but often these don't provide insight in to underlying mechanisms. In this paper, we present a model for compressible flow of gas that builds on a set of well-known equations. We also describe experiments to verify this model for a range of pressures and temperatures. Finally, we describe the applicability of this model to the operation of the actual NIF targets.

Theory and model

Our main objective here was to construct a compressible fluid flow model that accounts for the flow rate of gas through the micro-capillary fill-tubes. A full-blown model to describe compressible gas flow can be quite involved but here we simplify the scope of model by considering mainly the range of experimental parameters of interest for target operation. For example, the conduit for flow is only through a series of tubes, allowing us to focus on cylindrical geometries. The pressure differences driving the flow are reasonably small which limits the effects of compressibility and tends to keep the flow in the laminar flow regime. We assume that there is no unspecified temperature variability or fluctuation. To begin with, we ignore molecular flow effects and consider only continuum flow mechanics.

We start by considering that in the extreme of a vanishingly small pressure drop, the gas has no compressive force and behaves like a liquid. This flowrate, for laminar flow condition, is given by the well-established Hagen Poiseuille equation. For the case gas flow driven by small pressure differences, this equation has been modified to include compressibility effect by Prud'homme et al (1) using perturbation analysis. The modified volumetric flowrate Q can be expressed as

$$Q = \frac{\pi(P_0 - P_L)R^4}{8\mu L}[1 - \frac{1}{2}\varepsilon - (0.029\kappa)\varepsilon\beta + (0.029\kappa)\varepsilon^2\beta + (\frac{2}{3} + 0.0023\kappa^2)\varepsilon^2\beta^2 + ...] \quad (1)$$

where μ is viscosity, R is the inside radius, P_0 and P_L are the pressures at the beginning and end of the tube of length L, ρ_0 is the mass density of the fluid at P_0, $\beta=R/L$, $\varepsilon=(P_0-P_L)/P_L$, and $\kappa=R^3\rho_0(P_0-P_L)/L\mu$.

For a chamber (say the hohlraum or the capsule) of volume V_c at pressure P_c and temperature T_c and containing n_c moles of gas,

$$\frac{dn_c}{dt} = \frac{n_c(t)}{V_c}Q(n) \quad (2)$$

or

$$\frac{dP_c}{dt} = \frac{P_c}{V_c}Q \quad (3)$$

Integrating Equation (3), we get

$$\ln(P_c) + C = \frac{Q}{V_c} t \tag{4}$$

where the integration constant C depends on the initial boundary conditions and Q is given by Equation (1). This suggests an exponential decay or rise, as expected.

Using this, we can account for changes in the pressure and the moles of the gas in the hohlraum or the capsule for a range of parameters. However, the meaningfulness of the model results can only be confirmed by comparison to corresponding experimental data. Ideal gas law is known to work well for most gases, so the validity of Equation (4) depends largely on the accuracy of the Equation (1) to predict the flow rate.

In the following sections, we describe our experimental efforts. As mentioned above, it is not possible to measure the pressure inside the capsule or the hohlraum. But the above model, i.e. Equation (4), predicts transients in pressure for any chamber of known volume at a given temperature. We make use of a pressure measuring device with a fixed volume chamber, such as a capacitance manometer. The pressure of the gas in this volume can be measured at any time while being evacuated or filled through one or more micro-capillaries of interest. This data can then be directly compared to the output of the model. This can be done as a function of various parameters and serves to verify the validity of the model.

Experimental

Micro-capillaries used for testing had three different internal diameters (ID): 75 um, 30 um and 5 um, all of which are used on NIF targets. Metal tubing (320 um ID, 325mm long) was used to connect the micro-capillaries to standard VCR fittings on the front and the back end, consistent with NIF target assembly. The two larger diameter filltubes (75um and 30um) were polyimide coated silica micro-capillaries made by Polymicro Technologies. Both had a net outer diameter of 150 um including a 12um thick polyimide coating. Lengths used in the experiments were variable and are stated case by case.

The 5 um ID micro-capillary, from Humagen Fertility Diagnostics, had an outer diameter of 10 um and was comprised of uncoated borosilicate glass. In our experiments, it was used in the same way it is on a NIF target- a 3mm segment was attached to the end of a longer, 30um ID tubing. The 3 mm micro-capillary was actually slightly conical, with the ID going from 5 um to about 10 um from one end to the other. The 10 um end was inserted into the 30 um ID tubing and glued to make the junction leak-free. In a target, this composite tube serves as the capsule fill-tube.

The schematic of the experimental set-up is shown in Figure 1. The pressure monitoring device used was a Baratron Model 690 from MKS instruments, which has a volume of 2.5ccs. Its range was 1100 to 0.1 torr. The volume of the tubing connecting the Baratron to the micro-capillary was determined to have a volume of 0.9 ccs, so the total volume connected to the capillary was 3.4 ccs (V_c).

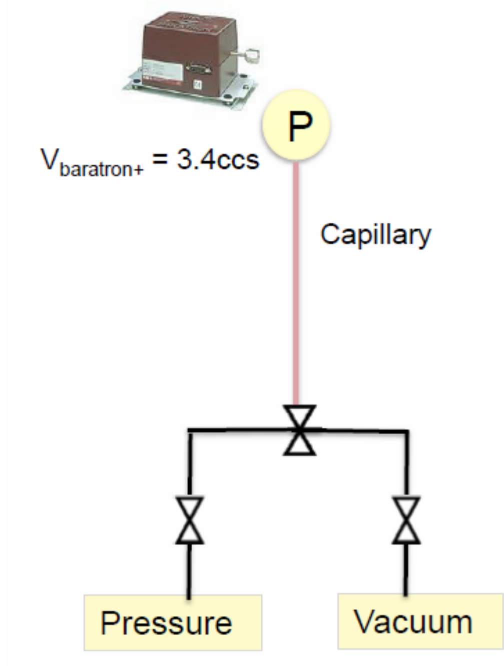

Figure 1: Schematic of the of the experimental setup

Experiments were done with the micro-capillary at room temperature as well as when it was fully submerged in LN (i.e. at 77K). Also, by extending the tubing between the Baratron and micro-capillary, the latter was placed in a cryostat and cooled to 19.5K, which is of interest for NIF operations.

Results and Discussion

Figure 2 shows the results obtained from air flow through a filltube (75um ID and 115mm long), both during evacuation and subsequent filling. It is immediately evident that evacuation is significantly slower than filling. This is to due to the fact that the density of the gas in the volume being vacuumed is constantly falling. We see that the model predicts the pressure quite well indicating that it accounts for the conductance of the filltube accurately over most of the pressure range. The highest Reynolds number, N_{Re}, during either the evacuation or the filling process is 1250, so the flow is laminar all throughout this experiment. Similar curves can be obtained by varying the length of the capillary or the diameter (such that the ratio of length to diameter was always high enough to have fully developed flow) and the general fit to the model was the same in each case. We note that there are no adjustable parameters in the model, so a good fit with data is a fair validation of the underlying equations.

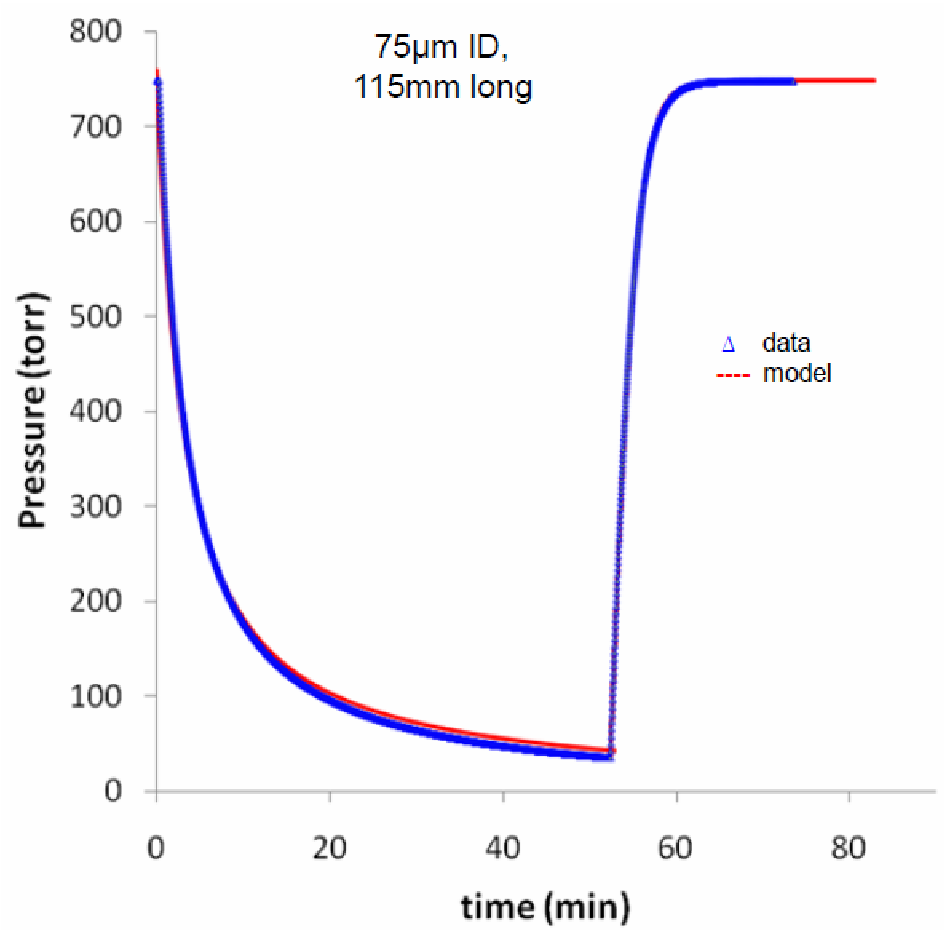

Figure 2: Results from model compared to data for air from a 3.4cc volume being evacuated and later filled with a 115mm long, 75 um ID micro-capillary at room temperature

We also see that, whereas the fit is good at the higher pressures, we begin to see a deviation during the evacuation process at lower pressures. There is no such deviation during the pressurization. So we can infer here that the model based continuum flow mechanics is adequate to describe the filling process (so long as P_o is at least 50 torr) but needs modification for the low pressure regime. When the evacuation pressure data is plotted on a semi-log scale, as seen in Figure 3, the deviation of the predicted pressure compared to actual is clear. By plotting with the Knudsen number K_n (defined here as the ratio of the mean free path λ to the capillary diameter D) as the abscissa, we find that the deviation starts at K_n =0.005. It is well known that Knudsen flow or free molecular flow occurs when the mean free path of the gas molecules approaches the characteristic physical size scale of the chamber. Given that the deviation we see is happening well below this, we need to consider the so-called transition flow regime. Indeed, if we model the flow using conventional Knudsen flow equation (2), we find that it over predicts the rate of decrease in pressure.

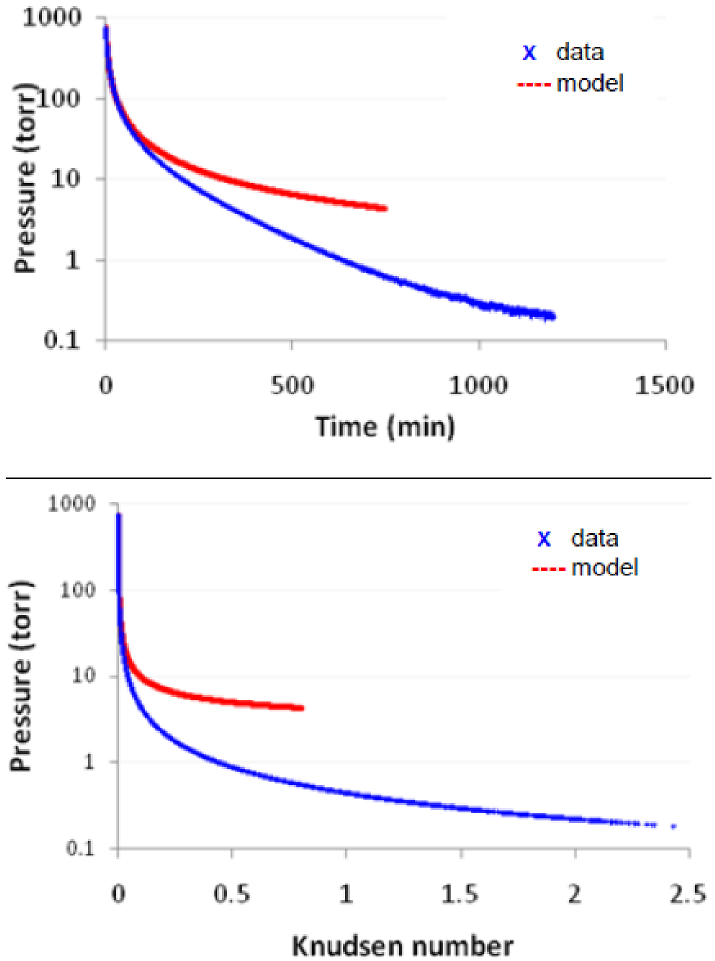

Figure 3: Results from model compared to data for air from a 3.4cc volume being evacuated with a 119mm long, 75 um ID micro-capillary at room temperature

Several different models for transition flow have been described in the literature (2-6). To pick the appropriate model among these, we have the benefit of being guided by our data, which indicates that the deviation of the simulated pressure from the data increases with K_n. This in turn implies that the capillary conductance increases with K_n. One model that describes transition flow regime where the flow rate is dependent on the magnitude of K_n is the slip flow equation. Viscous (or continuum) flow model uses a no-slip boundary condition at the wall of the tube. In free molecular flow, intermolecular collisions are ignored compared to the collisions with the wall. In the regime between these two mechanisms, the slip flow model calls for modification of the viscous flow with a small but non-zero tangential wall-velocity. In doing so, slip theory attempts to extend continuum flow mechanics with the following boundary conditions:

$$\frac{du}{dr} = 0$$

at r=0 (5)

where u is the local velocity and

$u=u_s$ at r=R (i.e. at the wall) (6)

The velocity at the wall, u_s, can be can be specified using the hypothesis that slip of the molecules along the wall could be attributed to specular reflection where the molecules do not transfer momentum to the wall. If f_s is the fraction of molecules that are diffusely reflected (and ($1-f_s$) is the fraction for specular), then u_s can be expressed as (first postulated by Millikan (7)):

$u_s=u(1-f_s/2)$ (7)

The resulting slip flowrate Q_s (8) is given by:

$$Q_s = Q\left(1+4(\frac{2}{f_s}-1)\right)\frac{\lambda}{R} \quad (8)$$

where λ is the molecular mean free path. Again, the significance of f_s is that it represents the fraction of molecules whose reflected velocity is unrelated to the incident velocity. The slip flow equation has a contribution to flow that is directly proportional to λ/R, which is $2K_n$. In contrast, the free molecular flow equation predicts a constant throughput independent of K_n, while continuum flow equation can be shown to predict a rate that is inversely proportional to K_n.

Substituting Equation 1 into equation 5, we get

$$Q_s = \frac{\pi(\Delta P)R^4}{8\mu L}\left[1-\frac{1}{2}\varepsilon-(0.029\kappa)\varepsilon\beta+\ldots\right]\left(1+4(\frac{2}{f_s}-1)\right)\frac{\lambda}{R} \quad (9)$$

Figure 4 shows the fit of the pressure prediction with the slip flow model to the same data seen in Figure 3. With the pressure is plotted on a log scale, we can see that slip flow equation fits the data very well down to 0.2 torr, below which point the resolution reliability of our Baratron gauge is questionable. Slip flow model requires specification of values for two new parameters- λ and f_s. The latter, f_s, and was specified so as to obtain the best fit. This value was 0.39 in this case. Specification of λ is discussed further below.

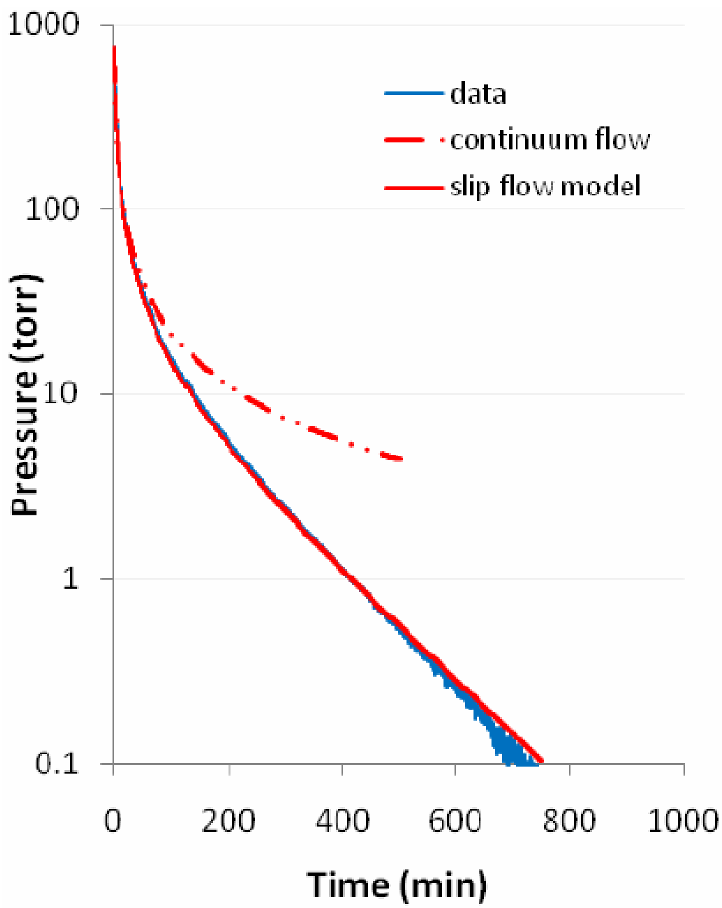

Figure 4: Results from two models, continuum and slip flow, compared to data for air from a 3.4cc volume being evacuated with a 119mm long, 75 um ID micro-capillary at room temperature

Kinetic theory of gases offers an equation for λ for a specified temperature and pressure as follows:

$$\lambda = \frac{k_B T}{\sqrt{2}\pi d^2 P} \tag{10}$$

where k_B is the Boltzmann constant, T is the temperature, P is the pressure and d is the diameter of the gas molecule. Molecular diameter d is available for pure gases such as He and Ar but is more difficult to specify for air. Here, we assume that the molecular diameter is the same as the hard sphere diameter. We found that the fit of the slip flow model to pressure-vs-time data for He (Figure 5) and Ar was excellent (within 1%) for same value of f_s (Table 1). Having determined the value for f_s, in the case of air we fit the data using the effective molecular diameter as an adjustable parameter. The resultant value d, 4.57A, for air compares closely to those reported by others in literature. We found the same trends upon varying the length of the capillary. We thus conclude that f_s, the fraction of diffuse reflectance events, is indeed constant for this micro-capillary and independent of the length and gas type. However, f_s was seen to be slightly lower (f_s=0.39) for the 75um ID micro-capillary compared to 30um ID (f_s=0.43). Both capillaries were comprised of silica. One possibility for this difference could be the difference in roughness of the inner surface of the capillary.

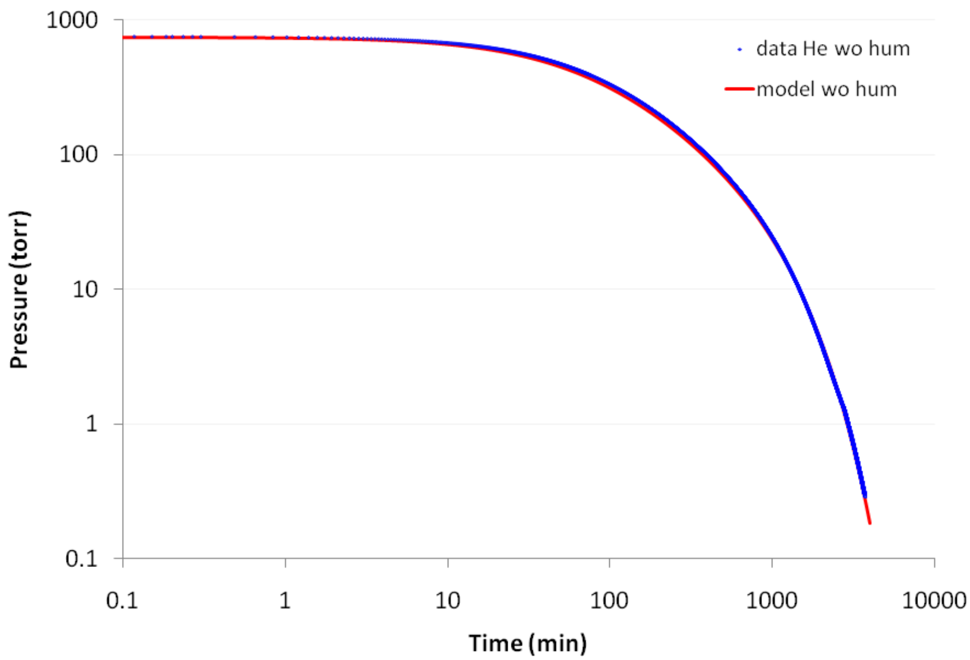

Figure 5: Results from slip flow model compared to data for He from a 3.4cc volume being evacuated with a 92 mm long, 30 um ID micro-capillary at room temperature

Table 1: Values for f_s and d that give a best fit with less than 1% deviation to the data. Fill-tube had a 30um ID and was 92 mm long.

	d (A)	**f_s**
He	2.56	0.43
Ar	4.0	0.43
Air	4.57	0.43

We point out one other interesting observation for the data shown in Figure 5. Because of the smaller diameter of the filltube (30um ID), the value of K_n at the lowest pressure is about 20. Even at this high a K_n value, slip flow model continues to fit the data remarkably well.

Figure 6 shows the results with the capillary (75um ID, 172mm long) at 77K, i.e. submerged in liquid nitrogen with non-condensable He as the gas. Note the significantly greater rate of pressure decrease. There are two reasons for this- the viscosity of helium is lower at 77K (0.00829 cP at 77K compared to 0.018 cP at 295K) and also the flowing gas is now denser. We used viscosities from NIST to model this case; common equations for determining viscosity as a function of temperature such as the Sutherland formula, were found to be inaccurate. Also seen in Figure 6 is the fit of the slip-flow model. In this case, the model has also taken into account the fact that temperature changes as the gas enters the micro-capillary, which is at 77K from a source (Baratron) at 295K. Here the fit is achieved using f_s of 0.51. Figure 7 shows the filling of He into a previously vacuumed Baratron at three different temperatures (295K, 77K and 19.5K) and the corresponding fit of the model. The volume to be filled is greater (94.5 ccs) due to the extra tubing required to include a cryostat in the set-up. As mentioned earlier, it is not necessary to use the slip flow model during the filling process. The Figure confirms the validity of the model over this range of temperatures.

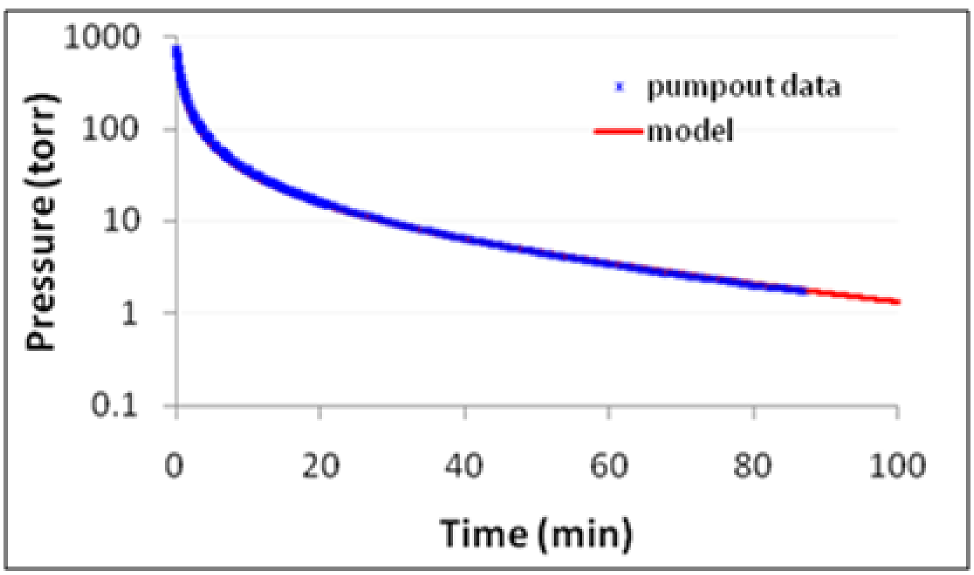

Figure 6: Results from slip flow model compared to data for He from a 3.4cc volume being evacuated with a 172 mm long, 75 um ID micro-capillary at 77K

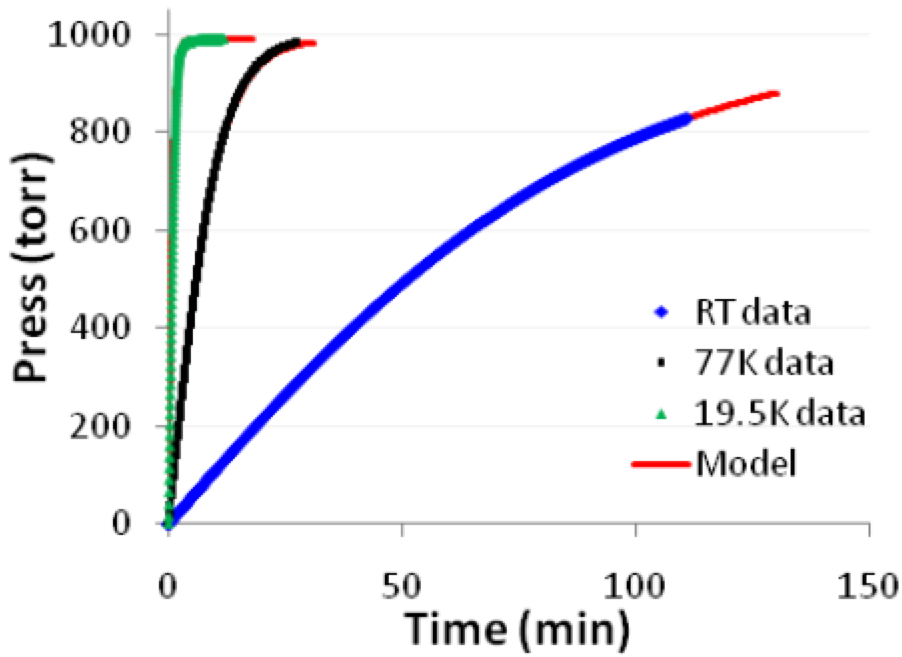

Figure 7: Results from model compared to data for He being filled into a 94.5 cc volume with a 172 mm long, 75 um ID micro-capillary at 295K, 77K and 19.5K

One more issue that is needs to be addressed for NIF targets is composite fill-tubes. For a composite tube of two different IDs and lengths, the sum of the pressure drops caused by each of the tubes equals the net pressure drop. By equating the flowrate through the individual tubes, one can derive an equation for that links the total pressure drop to that caused by one of the two tubes. For a composite filltube with tubes with internal radii R_1 and R_2 and lengths L_1 and L_2, we get:

$$\Delta P_2 = \frac{x R_1^{\,4} \Delta P}{(R_2^{\,4} + x R_1^{\,4})} \qquad (11)$$

where $x=L_2/L_1$.

Finally, we take in to consideration that the capsule fill-tube actually contains a slightly conical tube. The borosilicate micro-capillary used is made by drawing the glass at high temperatures and as a result, it flares out from 5um ID at the tip to 10 um 3 mm out. The simple way to address a conical tube is to use an effective radius approach. If R_0 and R_L are radii of a tube at length 0 and L, then the effective radius R_{eff} is

$$R_{eff} = R_0 \left[\frac{3\alpha^3}{1+\alpha+\alpha^2} \right]^{0.25} \qquad (12)$$

where $\alpha=R_0/R_L$.

These two equations can be substituted in Equation 1 or 9 to get the conductance of a composite tube with a conical section. In Figure 8, we show the fit of the model to the data for a composite fill-tube with a 30 um ID, 260mm long capillary joined to a conical borosilicate tube 3mm long, 5um ID at one end and 10um at the other. We find that the K_n for the model for this case is that for the 30um ID capillary.

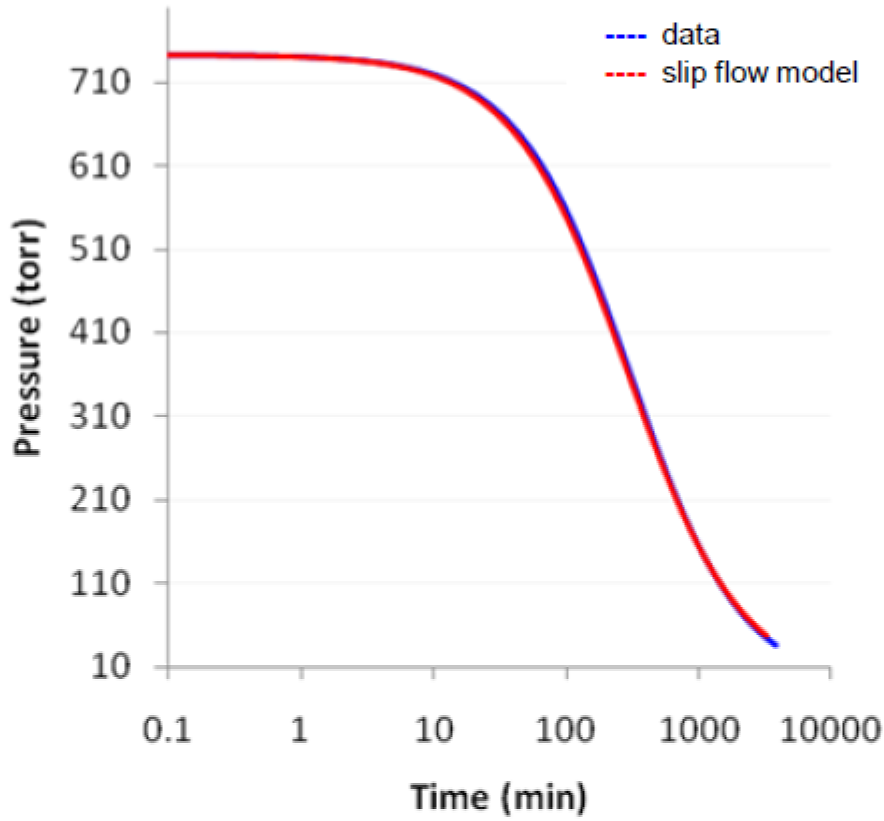

Figure 8: Results from slip flow model compared to data for He from a 3.4cc volume being evacuated with a composite tube with a conical section on one end at room temperature

Summary and Applications

In summary, our results show that we have a proven model capable of accurately simulating the conductance of the capillaries and the resultant changes of the moles and pressure of the gas in the chambers attached to these capillaries. The capability of the model includes range of pressures from 1000 torr to 0.1 torr and temperatures from ambient to 19K. The model can also account for composite tubes with more than one radius. We also present few important conclusions from this work regarding flow at lower pressures. We show that slip flow model provides a very good fit with data and that this equation agrees with data from very low K_n to values of K_n as high as 20. We also find a consistent value for f_s, the fraction of molecules undergoing diffuse reflectance at the wall of the conduit, over multiple experiments with different lengths and gas types such as He, Ar or air. This value changes slightly between the 75 um ID to the 30 um ID micro-capillaries, from 0.39 to 0.43 respectively. There is a greater change in f_s with temperature- from 0.39 at ambient to 0.51 at 77K for the 75um ID tube.

We have applied this to understand several aspects of the operation of the target, including field data from NIF. For a hohlraum volume of approximately 0.3ccs or a capsule volume of 4.5×10^{-3} ccs, the model predicts a pumpdown profile shown in Figure 9. Some examples are using this model to restrict the pressure difference between the inside and the outside of the hohlraum to 100 torr to avoid plastic stretching of the 500nm thick laser entry hole windows. We can use this model to evolve a deterministic pump-purge cycle recipe for the hohlraum and capsule to avoid ice-plugging during the cool-down on NIF. Since formvar tents are susceptible to radiation damage by tritium permeated from the capsule, it is important to limit the exposure time. We can model various conditions to achieve this optimally. Another example is the ability to predict the gas density in the capsule and the hohlraum as the target is quenched just before the laser shot.

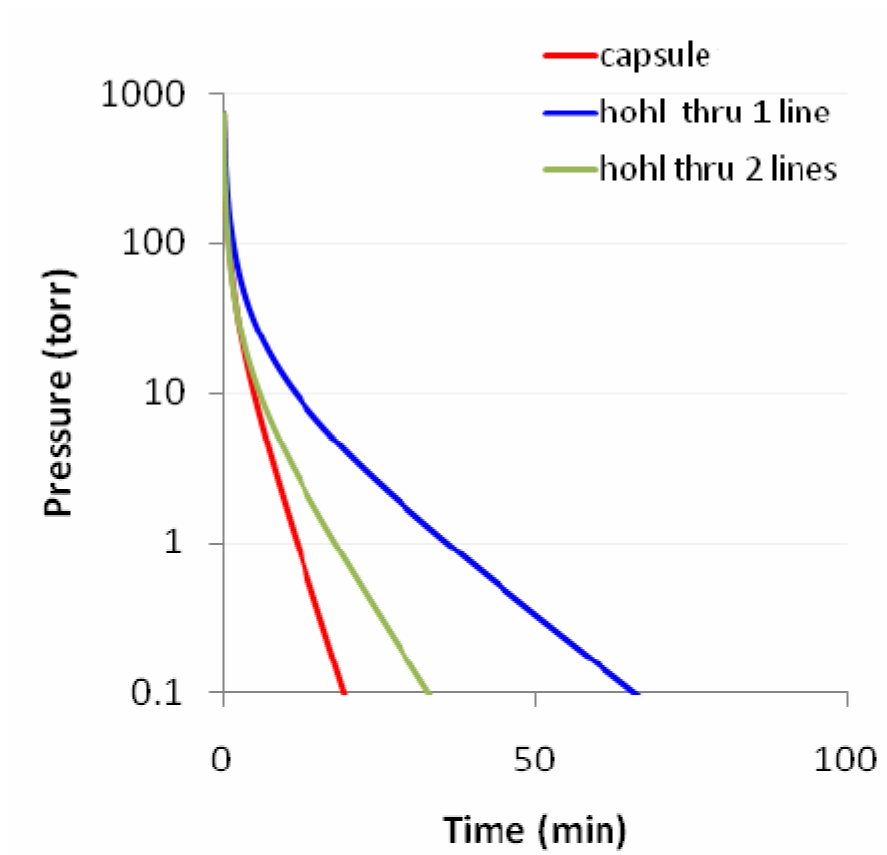

Figure 10: Pressure change profiles for evacuation of hohlraum and the capsule on NIF target at room temperature using the model that accounts for all the parameters

We show one example to illustrate that this model predicts the conditions in the hohlraum. Whereas we cannot directly measure the pressure in the hohlraum, we can look at the He permeation rate behavior, which is linearly proportional to He the pressure in the hohlraum. This occurs due to the presence of polymer windows used to seal the hohlraum's diagnostic view ports. The permeation rate timescale was found to be in the order of seconds. This was done by filling He in to the hohlraum through one of the laser entry holes on the end of the hohlraum. Thus there is impedance to the flow of the He into the hohlraum. As seen in Figure 10, the pressure in the hohlraum rises instantly to 50 torr as He is fed in. We see an immediate response on the He detector indicating permeation. As the He is vacuumed out, the permeation drop in essentially simultaneous. This implies that the permeation time-constant is in the order of a few seconds. In th second part of the experiment shown in Figure 10, we feed the He into a similar hohlraum but now through a 115 mm long, 75 um ID fill-tube. We use the model to predict the pressure rise in the hohlraum and compare that to the data for the permeation rate. The good agreement between the two indicates that the pressure rise predict by the model fits our observations. This is a repeatable and hence characteristic behavior of the hohlraum when filled with He through the fill-tube. In fact, we use this to weed out targets with partially plugged capillary tubes (due to debris) that show a deviation from the expected rise and fall profile.

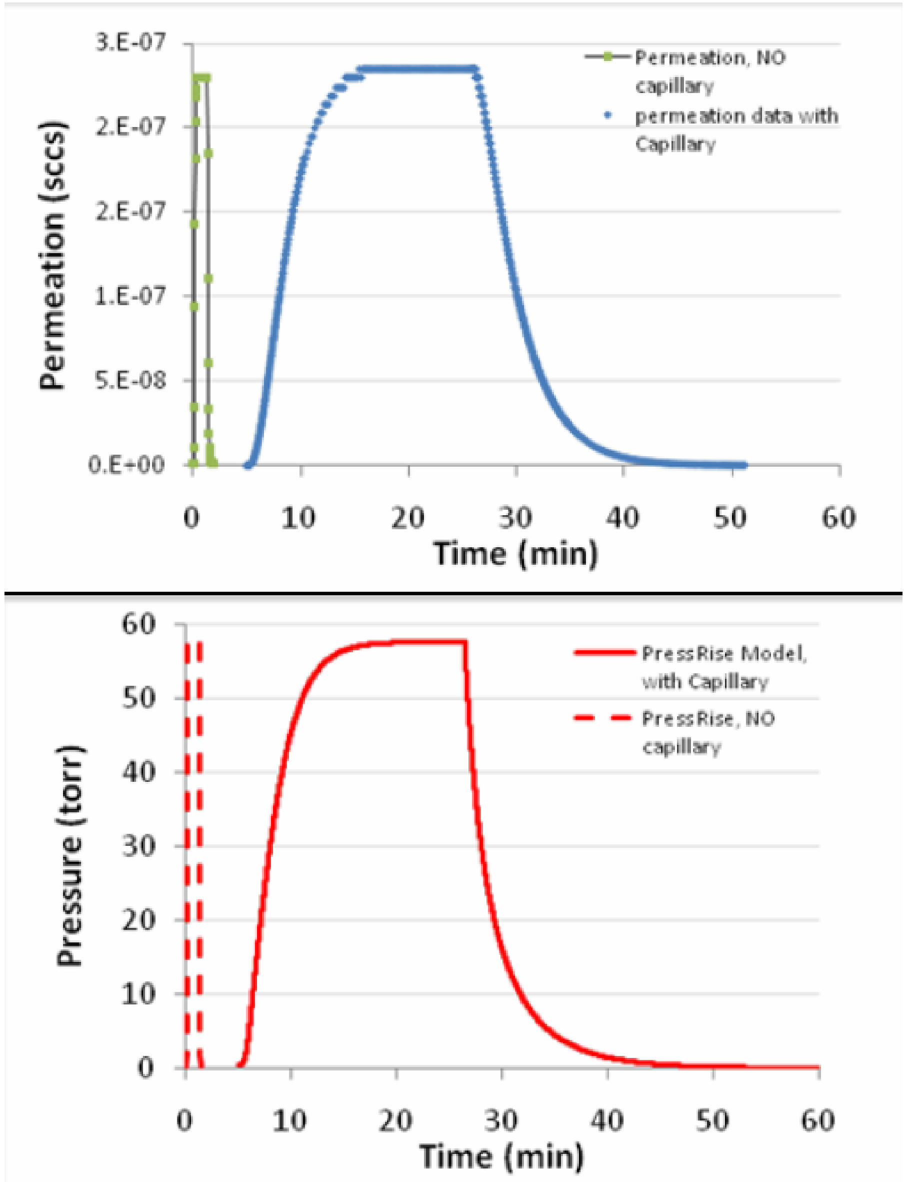

Figure 11: Data for the permeation of He shown on the top half of the figure. The second plot at the bottom shows the modeled rise in pressure inside the hohlraum.

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